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Mass Loss and Variability in Evolved Stars

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Abstract. Mass loss and variability are two linked, fundamental properties of evolved stars. In this paper I review our current understanding of these processes, with a particular focus on how observations and models are used to constrain reliable mass loss prescriptions for stellar evolution and population synthesis models.

1. Introduction

Stars are the alchemist’s dream: they are the nuclear furnaces transmuting the light nuclei from the dawn of the cosmos into the heavier elements found in planets and living organisms. It is only thanks to the process of *mass loss*, however, that these enriched elements are finally released to the InterStellar Medium (ISM), where they can form a new generation of stars, closing the loop in the galactic ecosystem. It is through mass loss that stars became the engines of galactic chemical evolution (see e.g. Tinsley 1968; Chiosi & Maeder 1986).

While mass loss processes are active in most evolutionary phases, they became especially efficient after the end of the main sequence. The basic principles driving the intense mass loss of evolved stars have been well recognized for over 4 decades (Salpeter 1974; Kwok 1975; Goldreich & Scoville 1976): as stars switch from core to shell nuclear burning, the added luminosity swells them to giant or supergiant radius, leading to low gravity and cool effective temperature. Their atmospheres are further destabilized by radial pulsations, induced as the stars cross the Long Period Variability (LPVs) instability strip. Shocks from the pulsations compress and levitate the tenuously bound external atmospheric layers, triggering an outflow. Particulates (astronomical dust) condensate (Sedlmayr 1994) and are pushed by stellar radiation pressure, dragging the molecular gas and further enhancing the wind. Through this mechanism, mass loss rates can reach values as high as $\sim 10^{-4} M_{\odot}/\text{yr}$ (see e.g. reviews by Habing 1996; Willson 2000). As shown in Figure 1, this combination of low g , low T_{eff} and pulsations happens twice in the life of low and intermediate mass stars ($M \lesssim 10 M_{\odot}$), as they climb back the Hayashi tracks during the Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB) phases. High mass stars instead cross the LPV instability strip as Red Supergiants (RSG).

Despite the importance of mass loss for both stellar and galactic evolution, many fine details of this process are unknown: we are still lacking a comprehensive framework capable of predicting mass loss rates from fundamental stellar parameters (M , L , R , $[\text{Fe}/\text{H}]$ and ℓ/H). This lack of knowledge poses severe limitations to our understanding of the last phases of stellar evolution: while the AGB phase is driven by the mass of the inert C/O degenerate core (Paczynski 1970), the end point is determined by the effi-

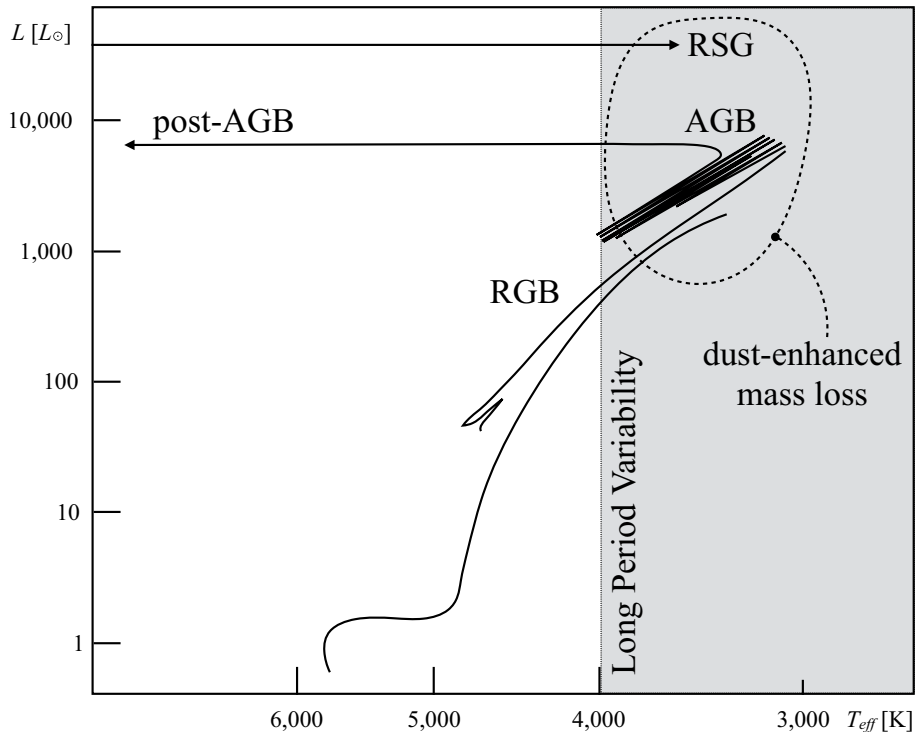


Figure 1. Schematic view of a $1 M_{\odot}$ star late evolutionary phases characterized by intense mass loss and variability. Evolutionary track adapted from Sackmann et al. (1993). The trajectory of a RSG star is indicated at the top of the diagram.

ciency of mass loss in depleting the convective envelope. Even a basic parameter such as the mass above which a star ends its life as a core-collapse supernova (SN), rather than an AGB, is very uncertain. The long held assumption that all AGBs are progenitors of White Dwarfs (WD) has recently been cast into doubt, with the hypothesis that *super*-AGBs (AGB stars in the $5\text{--}10 M_{\odot}$ range) could be the progenitors of dust-enshrouded, electron-capture SN (Thompson et al. 2009; Pumo et al. 2009). Similarly, the mass range of intrinsic carbon stars, and its dependence on zero age metallicity, has been the subject of intense investigation. Despite a general agreement between observations (see e.g. van Loon et al. 2005; Feast et al. 2006; Lebzelter & Wood 2007), and detailed evolutionary tracks (see e.g. Marigo & Girardi 2007), both lower and upper mass limits for the formation of carbon stars are still subject to revisions. At the lower end, raising the C/O ratio above unity depends on the efficiency of the third dredge-up during the Thermal Pulsing AGB phase (TP-AGB). At the upper end the C/O ratio is reverted below unity by the Hot Bottom Burning process (HBB; Bloeker & Schoenberner 1991; Boothroyd & Sackmann 1992), destroying the newly generated carbon in intermediate mass AGB stars. Both limits are affected by the depletion of the stellar convective envelope due to mass loss, which is uncertain. Finally, the initial-final mass relation derived from the analysis of cluster WDs, potentially providing strong constraints to the overall mass lost during the RGB and AGB phases, still suffers from a large scatter (compare e.g. Catalán et al. 2008; Kalirai et al. 2008; Salaris et al. 2009). All these uncertainties

pose serious difficulties for stellar population synthesis simulations requiring accurate estimates of stellar yields for galactic chemical evolution models.

In the last few years, however, significant progress has been made on several fronts, from the availability of new instrumentation ideally suited to measure the fine details of evolved star outflows, to the coming of age of a new generation of dynamical models simulating the processes at the base of mass loss, including the hydrodynamics of pulsations, and the condensation of dust. In this paper I will discuss the current state of affairs, with particular emphasis to the ongoing quest for a parametric representation of mass loss that can be employed in stellar evolution and population synthesis models.

2. Observational Constraints

Due to the large column density of dust enhanced winds, observation of mass-losing evolved stars have traditionally been the domain of infrared and sub-mm/radio telescopes (see e.g. Marengo 2009, for a review). Radio observations, in particular, are sensitive to the gas component of the outflow, and can provide reliable estimates of the circumstellar *gas* mass by spectrally resolving rotational transitions of molecular tracers, such as CO (see e.g. De Beck et al. 2010, for a recent survey). These observations have the advantage of directly measuring the outflow velocity, which is needed to convert the mass of the circumstellar molecular envelope into a mass loss rate (e.g. \dot{M}_{CO} into \dot{M}), but still rely on uncertain estimates of the molecular tracer abundance to derive the total mass loss \dot{M} of the star. Fitting the mid-IR excess with radiative transfer models, on the other hand, provides robust measurements of the circumstellar *dust* mass (see e.g. Groenewegen 2006; Sargent et al. 2010; Srinivasan et al. 2010), but not of the total mass loss rate, which still requires an independent knowledge of the kinematics of the envelope (the wind velocity) and of the gas to dust mass ratio. These free parameters are responsible for uncertainties in the total mass loss rate as large as one order of magnitude. Near-simultaneous radio/sub-mm/infrared observations provide the most stringent constraints to the mass loss parameters, but still suffer from the tendency of different tracers (multiple dust components and different molecular transitions) to be spatially segregated, and may probe different mass loss timescales.

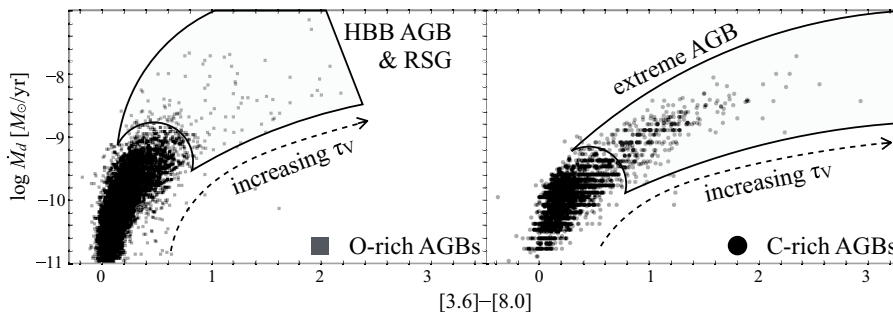


Figure 2. Dust mass loss rate vs. $[3.6]-[8.0]$ color for O-rich (*left*) and C-rich (*right*) AGB stars in the LMC, as calculated by Riebel et al. (2012) by fitting SAGE photometry on MACHO selected LPVs. Grey area indicate sources with high mass loss rate: intermediate mass AGBs undergoing HBB among the O-rich sources, and the so-called “extreme AGBs” among the C-rich stars. RSGs would be located in the same general area as the O-rich HBB sources.

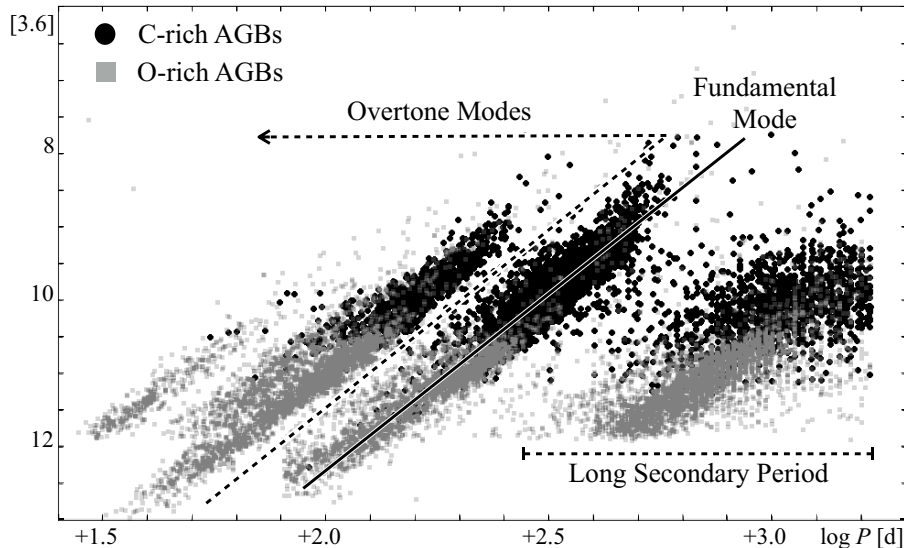


Figure 3. Period-Luminosity diagram of AGB stars in the LMC found by Riebel et al. (2012) by matching the SAGE catalog with MACHO lightcurves. The C/O dust chemistry of each source was determined by radiative transfer fitting of its optical and infrared SED.

The recent availability of deep photometric surveys covering entire galaxies in the near-IR (e.g. the VISTA Magellanic Cloud survey, VMC; Cioni et al. 2011) and in the mid-IR (e.g. the “Surveying the Agents of a Galaxy’s Evolution”, SAGE and SAGE-SMC surveys; Meixner et al. 2006; Gordon et al. 2011) opened the possibility of deriving dust mass loss rates \dot{M}_d for entire populations of evolved stars (Gullieuszik et al. 2012; Riebel et al. 2012). As an example, Figure 2 shows the correlation between mid-IR colors and \dot{M}_d for AGB stars in the LMC, based on the model fitting of SAGE data by Riebel et al. (2012). This approach, when applied systematically to different environments within the Galaxy (e.g. globular clusters and the bulge) and in galaxies within the local group, provides a direct handle on the dependence of dust abundance and mass loss rate from metallicity (see e.g. the “DUST in Nearby Galaxies with Spitzer”, DUSTiNGS, targeting 50 local group dwarf galaxies with Spitzer; Boyer et al. 2014). This technique is also crucial to understand the yield of stellar mass loss to the overall dust budget in galaxies (Matsuura et al. 2009; Boyer et al. 2012; Riebel et al. 2012; Zhukovska & Henning 2013).

Optical surveys, meanwhile, have been targeting the time domain. The MACHO (Alcock et al. 1996) and OGLE-III (Udalski et al. 2008) surveys, in particular, have collected lightcurves for thousands of LPVs in the Magellanic Clouds. Combined with infrared photometric surveys, these lightcurves allow the characterization of evolved stars according to their pulsation properties, establishing the link between variability and mass loss. A typical example is shown in Figure 3, where AGB stars in the LMC self-organize in separate Period-Luminosity (PL) sequences based on their pulsation mode. These sequences, first described by Wood (2010), separate fundamental mode pulsators from first and higher order overtone pulsators, as well as from a class of “secondary long period” variables whose nature is uncertain. The PL sequences in Figure 3 offer a more quantitative diagnostics to characterize the pulsation properties of LPVs

than the traditional *Mira* (which pulsate in fundamental mode) vs. *semiregular* (both fundamental and overtone) dichotomy. The lack of reliable distances hinders similar analysis for galactic LPVs (whose parallaxes are notoriously difficult to measure), even though efforts have been made in this direction (see e.g. Tabur et al. 2010).

The detailed physical processes responsible for mass loss, on the other hand, can be uniquely studied using interferometric techniques in the infrared (VLTI), sub-mm (SMA and now ALMA) and radio (EVLA, VLBI). The high angular resolution achieved with interferometers enables precision measurements in the circumstellar molecular layers where the dust is condensed and the wind accelerated (see Wittkowski review in this volume). These observations provide strong constraints to models by spatially resolving the dust condensation sequence and the asymmetries within the MOLsphere (the extended molecular gas atmosphere) of pulsating giant stars (see e.g. Karovicova et al. 2013; Sacuto et al. 2013), aided by the wealth of spectral data collected by Herschel (e.g. Lombaert et al. 2013; Khouiri et al. 2014), and thermal infrared spectrograph on ground-based telescopes and onboard SOFIA. Significant progress is to be expected in this field in the near future, as aperture synthesis image reconstruction in the near- and mid-IR is coming to age, and as a new generation of VLTI instrument is being developed (MATISSE, GRAVITY).

Finally, temporal variations in the mass loss rate are constrained by wide field imaging of nearby stars, either in visible scattered light (e.g. Maun et al. 2013), in the UV (Martin et al. 2007; Sahai & Chronopoulos 2010), in the infrared (most recently with Herschel, e.g. Cox et al. 2012), in the radio (Matthews et al. 2013) and in the sub-mm with ALMA (Maercker et al. 2014). These observations also provide unique information on how the stellar outflow interacts with the ISM, and allow resolving the degeneracy between morphology, temperature and density in radiative transfer modeling, leading to more accurate estimates of the mass loss rate.

3. Mass Loss Modeling

A complete understanding of the physical principles behind mass loss in evolved stars has proven to be elusive, due to the complex interplay between molecular chemistry (some of which requires non-LTE treatment, see e.g. Ryde et al. 2014), dust condensation and growth, non-linear dynamics of the pulsations and wavelength-dependent radiative transfer.

Despite these difficulties, significant progress has been made in the last decade. Pioneering dynamic models were based on a crude treatment of grey radiative transfer (Bowen 1988; Hoefner & Dorfi 1997; Winters et al. 2000). Realistic spectra capable of reproducing the optical and infrared observations of LPVs only appeared when models started to include frequency-dependent radiative transfer (Höfner et al. 2003), and the complex chemistry network leading to dust condensation and growth (e.g. Gail 1998). While these models were initially using mass loss as a boundary condition, in order to determine the emerging spectra based on a prescribed dust production rate, the situation has much improved in the latest generation of models. For the first time, models are capable to produce synthetic mass loss rate predictions in both C and O-rich environment (e.g. Mattsson et al. 2008, 2010; Eriksson et al. 2014), taking full advantage of the wealth of observational constraints described in Section 2 and allowing to explore the dependence of mass loss from stellar parameters.

One point where dynamic models still lack fundamental physics is in the treatment of pulsations, which are forced by introducing a parametrized “piston” providing the boundary conditions at the base of the atmosphere. While this treatment is very effective in reproducing the light curves of individual LPVs, and allows exploring the effects of variability on mass loss rate, the lack of physical understanding of LPV pulsations is an obstacle for population synthesis models where the pulsation parameters of the evolved stars are not known a priori. Progress in this sense may come from 3D dynamic models (see Freytag & Höfner 2008; Chiavassa & Freytag 2014): while these models don’t yet include the physics of pulsations, they appear to spontaneously generate radial shocks that propagate and levitate the stellar atmosphere almost to the escape velocity. These results offer some hope that once the proper physics is introduced in the stellar layers that drive the pulsations, we may reach a better understanding of the LPV instability strip, and its effects on evolved stars mass loss.

4. Mass Loss Parametrizations

Evolutionary models require a reliable mass loss prescription in order to calculate the mass of the convective envelope on top of the nuclear-burning shells. As mentioned in Section 1, knowing the mass loss rate at any point during the RGB, AGB and RSG is crucial to determine the ultimate fate of the star (WD or SN) and the yield to the ISM.

In absence of dust enhancement the mass loss of evolved stars is generally described by equating the wind kinetic energy with the radiative flux and the gravitational energy. The original formulation (Reimers 1975) of such a law was derived by estimating the mass loss rate and wind velocity from circumstellar lines (Ca II H & K) in a magnitude-limited sample of optically-bright M giants:

$$\dot{M}_R = 1.34 \times 10^{-5} \eta \frac{L^{3/2}}{M T_{eff}^2} \quad (1)$$

were L and M are expressed in solar units, T_{eff} in K, \dot{M} in M_\odot/yr and the efficiency parameter η is calibrated by fitting the Horizontal Branch (HB) of globular clusters. As pointed out by the author, Reimers-type scaling relations are not appropriate to describe the intense winds characteristic of dust-enshrouded evolved stars in the TP-AGB phase. Modifications are required to reach the high mass loss rates of dust enhanced winds (e.g. Bloeker 1995) and describe the increasing mass loss rate of a star as it evolves along the AGB or supergiant branches.

A different approach is followed in the Vassiliadis & Wood (1993) mass loss prescription, that tackles the issue of mass loss during the AGB phase. The mass loss rate was in this case determined from either CO line emission (for LPVs with $P \lesssim 500$ days) or from infrared excess (IRAS data) for dust enshrouded variables (mostly OH/IR stars) with longer periods. The break at $P \sim 500$ days is reflected in the dependence of \dot{M} from the pulsation period. For stars with $P \lesssim 500$ days \dot{M} is a steep power law of the period

$$\begin{cases} \log \dot{M} = -11.4 + 0.0123 P & \text{for } M \lesssim 2.5 M_\odot \\ \log \dot{M} = -11.4 + 0.0125 [P - 100(M/M_\odot - 2.5)] & \text{for } M > 2.5 M_\odot \end{cases} \quad (2)$$

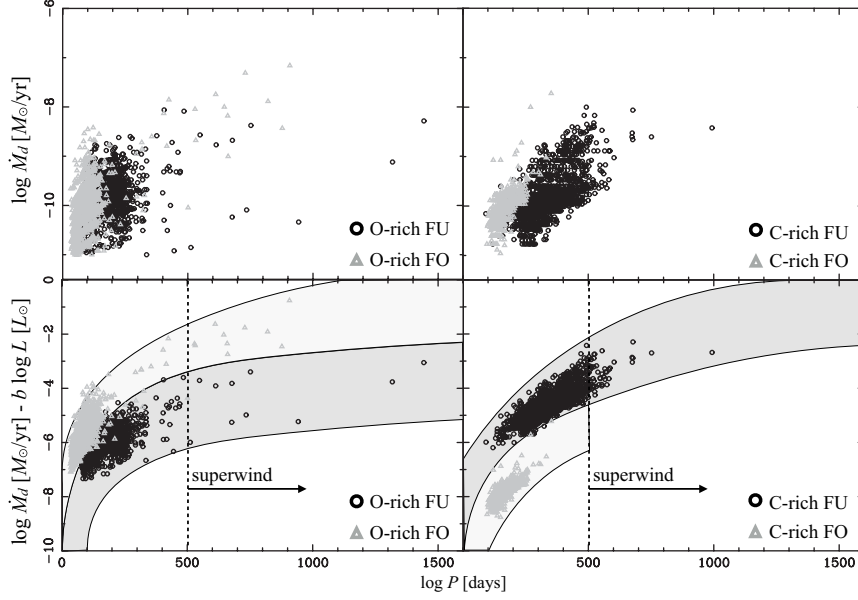


Figure 4. Mass loss vs. period for LMC AGB stars, separately for O-rich (*left*) and C-rich (*right*) sources. Dark circles are variables selected from the fundamental mode sequence in Figure 3, while grey triangles are selected from the first overtone sequence. The mass loss vs. period relation can be tightened by factorizing the luminosity along each pulsation sequence (*bottom* panels).

with \dot{M} in M_{\odot}/yr and P in days. For very long period variables the $\log \dot{M}$ vs. P relation flattens, with stars entering a *superwind* phase with $\dot{M} \approx 10^{-4} M_{\odot}/\text{yr}$. In Vassiliadis & Wood the dependence of the mass loss rate from R and L is implicit, as derived from pulsation theory (e.g. Wood 1990).

Stellar population synthesis models use a variety of mass loss prescriptions to parametrize mass loss in different evolutionary phases. A “state of the art” example is found in Rosenfield et al. (2014). A *pre-dust* phase characteristic of the RGB and early-AGB, when the wind is entirely pulsation-driven, are described by modern formulations of the Reimers wind, modified to take into account the role of Alfvén waves, the residual RGB envelope mass and MHD turbulence in convective zones (Schröder & Cuntz 2005; Cranmer & Saar 2011). Once dust appears the mass loss switches to an *exponential* mode, where the pulsation-driven mass loss is enhanced by radiation pressure on the dust grains. This is a Vassiliadis & Wood wind of the form $\dot{M} \propto R^a M^b$. The latest evolutionary phases on the AGB and RSG are then described by a *superwind* phase, as in Vassiliadis & Wood (1993), characteristic of stars falling over the mass loss “cliff” at the end of their life, rapidly depleting their convective envelope.

Much remains to be done. Current mass loss prescriptions do not effectively take into account the different dust and molecular chemistry in O-rich and C-rich evolved stars, despite evidence that the third dredge-up does affect not just the infrared colors of the circumstellar envelope, but also the mass loss rate (see e.g. Uttenthaler 2013). The large datasets provided by infrared surveys such as SAGE, offer a unique possibility for determining a robust parametrization of \dot{M} according to the pulsation mode and outflow chemistry. An example is shown in Figure 4, showing $\log \dot{M}_d$

(from the Riebel et al. 2012 SED fitting) vs. P (*top* panels). The relation can be significantly tightened (*bottom* panels) by factorizing the bolometric luminosity of each source (again from Riebel et al. 2012 fit) with a powerlaw L^b (with the exponent b determined individually for each pulsation sequence and chemical type). Note that the artificial break at $P \sim 500$ days, for superwind onset in the Vassiliadis & Wood mass loss, disappears in this parametrized space, and the sources align on a single sequence $\log \dot{M}_d = a \log P + b \log L$. Further work is however necessary to extend this dataset (which depends on accurate period determinations from the optical MACHO survey) to the most obscured sources (the extreme AGBs) at long periods. Efforts to fill this gap by measuring the complete lightcurve of very red LPVs in the LMC are the subject of a number of current Spitzer programs (e.g. PID 10154, PI B. Sargent).

5. Conclusions

The availability of large scale photometric surveys has provided the datasets required to explore the relation between mass loss and variability in complete samples of evolved stars in entire galaxies. Combined with recent development in high resolution imaging and spectroscopy of the molecular layers in mass losing stars, these observational efforts are providing uniquely strong constraints for a new generation of models capable to predict dust formation and mass loss rates from the fundamental physics of cool pulsating atmospheres. The ultimate goal is the generation of reliable mass loss prescriptions for accurate stellar evolution and population synthesis simulations.

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